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II. EXPERIMENTAL ANALYSIS

by

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EFFECT OF PROPAGATION ATTENUATION OF THIN FILM WAVEGUIDE ON OPTICAL THIN FILM LOSSES. II. EXPERIMENTAL ANALYSIS

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Abstract: The article presents methods of studying optical thin film losses from guided wave propagation attenuation of thin films, from an experimental approach. Moreover, some measurement results of low losses in optical thin film specimens are used to explain the sensitivity and superiority of this method in loss research.

Key words: optical loss, thin film, waveguide, light scattering, light absorption.

I. Introduction

As pointed out in the previous article on theoretical analysis [1], guided wave propagation loss in thin films can sufficiently reveal the magnitudes of absorption and scattering

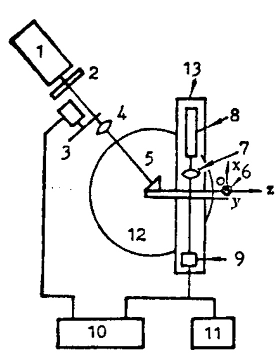
losses of thin films. Moreover, theoretical analysis is used on how to utilize propagation attenuations of various thin film guide modes in studying and analyzing thin film losses. Concretely speaking, various deficiencies of thin films are used to deal with different properties of propagation attenuation function; by utilizing the method of extrapolating the 90^0 propagation angle to isolate absorption loss in thin films, thus we determine the scattering losses of various guide modes of the thin film. Since there is greater interaction distance between the guided wave propagation and thin film medium in the thin film, the various deficiencies in the thin film can be sufficiently manifested in guided wave attenuation propagation. Therefore, guided wave propagation attenuation can sensitively indicate the situations of various losses in the thin film. For high-quality optical thin films, this is a very good method of research in analyzing losses.

From the experimental approach, the article will present manifestation methods of this loss analysis technique. Moreover, from the results of experimental testing, the superiority and potential application of this analytical technique are discussed in thin film studies.

II. Experimental Setup

Optothermal deviating refractive technique [2] is a technique used to study weak absorption or the thermal properties

of materials. The technique can very sensitively detect weak absorption of thin film or bulk materials. The principle is as follows: a specimen generates a heat effect with absorption of illuminated light; this heat effect will change the refractive index of the specimen and the surrounding media, forming a certain trapezoidal distribution of the refractive index. When another beam of detecting light passes through the medium with the trapezoidal distribution of the refractive index, deviating refraction of the light beam will occur. Based on the magnitude of the deviating refraction, the absorption magnitude of the specimen can be determined. By utilizing the optothermal deviating refractive technique for its effect on absorption sensitivity, and combining with the optical waveguide technique, the authors built an experimental setup as shown in Fig. 1.



1—Pump Laser
2—Half Wavelength Plate
3—Chopper
4—Lens l_1
5—Prism *P*
6—Sample
7—Lens l_2
8—Probe Laser
9—Position Detector
10—Lock-in
11—Voltmeter
12—Rotational plate
13—Displacing Table

Fig. 1 Schema of the experimental set-up

This experimental setup is composed of two relatively independent systems: optical waveguide system and optothermal detection system. In the optical waveguide system, a beam of a 25mW He-Ne laser passes through a lambda/2 glass wedge and

modulator; after the laser beam is focussed by lens l_1, the beam is coupled by the lens P on the thin film specimen pressed onto the rectangular surface of the lens. A beam of guided wave light (pumping light) is formed in the thin film as the beam propagates along the direction Oz. In the optothermal detection system, emitted from a 100mW He-Ne laser device, a detecting light beam passes through lens l_2 and is focussed on the surface of the thin film specimen. A detector quadrantly positioned detects the position of the light spots of the light beam after it passes through the specimen. The entire optothermal detection system is installed on a guided rail, and can move along two directions (OY and OZ) with respect to the optical waveguide system. The optothermal detection system can also synchronously rotate with the optical waveguide system with respect to the pumping laser device so that the detection light beam is consistently perpendicular to the specimen surface at different guide modes. After reducing by using the output signals of the quadrantly positioned detector, the detection light beam and the output signals (acting as the reference signal) of the modulator input together into a phase locked amplifier in order to eliminate slight deviating refraction of the detection light beam, thus measured from the noise.

In detecting, the optical waveguide system should be adjusted in order to excite the expected guide mode from the thin

film. Then the optothermal detection system is moved along the direction OZ to detect the variation in the guided wave propagation distance in the thin film as caused by the optothermal signals. Since the magnitude of the optothermal signals at a certain position is proportional to light intensity of the guided wave light at that position, thus, the variation of the guide wave propagation distance by the optothermal signals can be utilized to calculate the propagation attenuation of the guided waves in thin films during propagation. After testing all guided mode propagation attenuation in thin-film specimens, the properties of propagation attenuations of various guide modes with variation of guide mode propagation angles, can be utilized to further analyze the loss signals in the thin film.

We have to point out that the method of using propagation attenuation to analyze loss in thin film specimens can be adaptable to studying those thin film specimens with low losses. Because the greater the losses of thin film specimens, the shorter is the propagation distance of the guided wave light in thin films. For specimens with light extinction coefficient k_f greater than 10^{-4} in a thin film, since the propagation distance of the guided wave is too short, human eyes are almost unable to observe the guided waves propagated in the thin film [3]. However, for thin film specimens with high quality and low losses, this analytical technique has its unique superiorities.

III. Analysis of Experimental Results

By applying the above-mentioned experimental setup, measurements and tests were conducted on guide mode propagation attenuation of some high-quality low-loss thin film specimens. All specimens measured were Ta_2O_5 thin film specimens coated with the ion coating technique of low voltage high current. These specimens had very high focusing density with high film adhesive force, low loss, and good uniformity. Therefore, this is a new thin film deposition technique with very good prospects of application [4]. Since the specimens coated with this deposition technique have low losses, therefore their loss properties are very difficult to measure by using traditional methods. In the following, the authors will utilize the sensitivity of thin film loss by propagation attenuation of guided wave light in the thin film; by using the analytical technique of guide mode propagation attenuation, the loss properties of low-loss thin film specimens were studied.

First, measurements and test analysis were conducted on two Ta_2O_5 thin film specimens of the same optical thickness (both of 6lambda/4, lambda=6328Angstroms). Such specimens have two TE modes and two TM modes with respect to 632.8nm light. The test results are listed in Table 1, indicating great difference in attenuations in two specimens. The attenuation of specimen No. 2 is much weaker than that of specimen No. 1 with the corresponding

guide mode. Therefore, the thin film loss of specimen No. 2 is lower than that of specimen No. 1. However, which kind of loss is smaller? The answer can be explained with an analysis of magnitude in absorption loss and scattering loss in their constituents during the guide mode attenuation of the thin film. By applying the analytical method presented in reference [1], and by extrapolation of the value of the attenuation coefficient to the 90^0 propagation angle, the light extinction coefficient of the thin film can be determined, thus determining the attenuation corresponding to scattering loss of various guide modes. Table 2 shows the analytical results. It is shown that the light extinction coefficient of thin film specimen No. 2 is much smaller than that of specimen No. 1; this is the main reason that attenuation of specimen No. 1 is higher than that of specimen No. 2. Since scattering loss has a great effect on propagation attenuation of high-level guide modes, we can discover, by comparing the results of scattering loss of both specimens the following: the attenuation values of the TE 1 mode and TM 1 mode of specimen No. 1 are much higher than the attenuation values of specimen No. 2 with the corresponding modes. Therefore we can deduce that the scattering loss of specimen No. 1 is also greater than that of specimen No. 2.

TABLE 1. Measured Attenuations for Two Ta_2O_5 Thin Samples (dB/cm)*

mode	san ple 1	sample 2
TE0	23.5 (±0.6)	9.1 (±0.3)
TE1	35.6 (±1.0)	14.6 (±0.8)
TM0	21.9 (±0.6)	11.4 (±0.8)
TM1	38.9 (±1.6)	17.9 (±0.7)

* the data in parentheses means the measurement accuracy.

TABLE 2. Analyzing the Results of These Two Film Samples

	sample 1	sample 2
extinction coefficient	2.3×10^{-5}	9.9×10^{-6}
scattering loss (dB/cm)	TE0 1.8 (±0.6) TE1 10.1 (±1.0) TM0 1.7 (±0.6) TM1 10.4 (±1.6)	TE0 1.0 (±0.3) TE1 2.4 (±0.8) TM0 1.6 (±0.8) TM1 7.0 (±0.7)

The above-mentioned experimental results show that the study of optical thin film loss by using guide mode attenuation is not only feasible, but also can show loss properties from absorption and scattering, along with high sensitivity. Therefore, guide wave propagation attenuation can be used to study the effect of environmental change to thin film loss performance. Often, the effect due to environmental change in thin films is very weak; the previous detection methods are very difficult to indicate such changes in thin film specimens.

The authors studied the effect on loss performance of Ta_2O_5 thin film specimens with the baking technique. Both the

discussed thin film specimens of different thickness were baked for 24h at 200^{0}C in the atmosphere. Table 3 lists the test results of propagation attenuation of various guide modes before and after baking for both specimens. Table 4 lists the analytical results of absorption and scattering losses before and after baking for both specimens. As indicated by the test results, although the properties of optical spectral properties of both specimens are not appreciably different before and after baking; however, the propagation attenuations of both specimens did change quite obviously before and after baking. As explained in the results shown in Table 3, baking reduces the propagation attenuation of Ta_2O_5 thin film specimens by nearly one-half. As indicated, with the further analytical results in Table 4 concerning guide mode propagation attenuation, although the light extinction coefficient of the specimens before and after baking only changed in the magnitude of 10^{-5}, however, the propagation attenuation of various specimen guide modes showed great changes. This again explains, from another angle, that the propagation attenuation has high sensitivity when this attenuation is used to indicate parameters of slight structural change of the thin film structure. By carefully analyzing the results in Table 4, we can discover that the change in light extinction coefficients before and after baking is the main reason for causing change in the propagation attenuation of the guide modes. On the other hand,

Table 3 Attenuations measured before and after annealing (dB/cm)

	mode	before annealing	after annealing
sample (a)	TE 0	52.4 (±2.1)	20.9 (±0.8)
	TE 1	69.3 (±2.7)	30.1 (±1.5)
	TM 0	57.8 (±2.0)	22.8 (±0.8)
	TM 1	75.5 (±6.9)	32.0 (±1.6)
sample (b)	TE 0	30.7 (±0.9)	10.1 (±0.2)
	TE 1	30.5 (±1.1)	12.0 (±0.3)
	TE 2	37.3 (±1.5)	15.5 (±0.6)
	TM 0	30.0 (±0.8)	10.0 (±0.3)
	TM 1	32.0 (±1.4)	10.1 (±0.4)
	TM 2	40.8 (±1.2)	14.0 (±0.5)
	TM 3	55.0 (±3.5)	16.2 (±0.7)

Table 4 Analysing results of the loss after annealing

		before annealing	after annealing
sample (a)	extinction coefficient	5.7×10^{-5}	2.1×10^{-5}
	scattering loss (dB/cm)	TE 0 0.7 (±2.1)	TE 0 0.7 (±0.8)
		TE 1 3.0 (±2.7)	TE 1 4.4 (±1.5)
		TM 0 5.7 (±2.0)	TM 0 2.7 (±0.8)
		TM 1 8.0 (±6.9)	TM 1 6.0 (±1.6)
sample (b)	extinction coefficient	3.3×10^{-5}	1.1×10^{-5}
	scattering loss (dB/cm)	TE 0 1.5 (±0.9)	TE 0 0.2 (±0.2)
		TE 1 0.6 (±1.1)	TE 1 2.0 (±0.3)
		TE 2 4.2 (±1.5)	TE 2 4.5 (±0.6)
		TM 0 1.0 (±0.8)	TM 0 0.4 (±0.3)
		TM 1 2.0 (±1.4)	TM 1 0.2 (±0.4)
		TM 2 8.0 (±1.2)	TM 2 3.2 (±0.5)
		TM 3 16.2 (±3.5)	TM 3 3.3 (±0.7)

we should take note that the change also occurs in scattering loss of a guide mode before and after baking; however, its regularity is not as apparent as that of the light extinction

coefficient. All these phenomena indicate that loss constituent change occurs in thin film specimens before and after baking. The causes of these changes are very complicated: maybe while baking, oxygen in air imparts certain functions to these oxide thin films. Or, at high temperature, this is the result of speeding up crystal lattice oscillations in the thin film media, and so on. Whatever the cause, this sensitive analytical technique of thin film loss provides a new route for studying the loss mechanism of thin films.

IV. Conclusions

By utilizing the propagation attenuation of guide modes in thin films, the performances of optical thin films and the loss properties can be sensitively and fully expressed. In this article, the analytical method of propagation attenuation can be conveniently applied to simultaneously obtain information on absorption and scattering losses of optical thin films. This study and analytical technique is very important to research and fabrication of high-quality optical thin films. Besides, the method of analyzing thin film loss from attenuation extent is also adaptable to integrated optics and optical waveguides. We should point out the following: if this analytical method is combined with other testing means, it is possible to make further analysis and study of the bulk effect (bulk scattering) of thin films. This will provide new effective analytical means for the

connection between microstructure and macroscopic properties of thin films. These activities are to be further and extensively studied.

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